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Azimuthal and Transverse Single Spin Asymmetries in Hadronic Collisions [1]

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Abstract. We give a short overview of the phenomenology of azimuthal and transverse single spin asymmetries in (un)polarized high-energy hadronic collisions. We briefly summarize a transverse momentum dependent, generalized parton model approach to these polarization phenomena, and discuss some of its applications. Finally, open points and future developments will be outlined.

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INTRODUCTION

It was an early common belief that transverse spin effects should play a negligible role in high-energy hadronic reactions [1]. There are however several transverse spin effects which strongly contradict this theoretical prejudice. Typical examples are: a) The quark transversity distribution; b) The large transverse polarization of hyperons produced in unpolarized fixed-target pN collisions; c) The puzzling spin-spin correlations observed in pp elastic scattering; d) The huge transverse single spin asymmetries (SSAs) measured in the forward production of pions in polarized pp collisions; e) Several azimuthal asymmetries measured in (un)polarized Drell-Yan (DY) processes, in semi-inclusive deeply inelastic scattering (SIDIS) and in correlated meson-pair production in unpolarized e^+e^- collisions.

In this contribution we will concentrate on azimuthal and transverse single spin asymmetries in hadronic collisions, discussing recent theoretical and phenomenological progress in the framework of the so-called transverse momentum dependent (TMD) QCD approach, which offers a good description and a clear understanding of most of these phenomena. Within this approach, a new class of leading-twist, intrinsic transverse momentum dependent, polarized partonic distributions and fragmentation functions are introduced which play a fundamental role in spin physics. These TMD distributions are intimately related to several topics of increasing interest in hadronic physics: a) The parton orbital motion and angular momentum inside hadrons; b) The study of hadron structure in the impact parameter space; c) The nucleon generalized parton distributions and deeply virtual Compton scattering; d) The light-cone hadron wave functions.

In the sequel we will first summarize the phenomenological motivations behind these theoretical developments. We will then give a brief discussion of a generalized parton model approach, with the inclusion of intrinsic parton motion and polarization effects, which has been and is quite successful in explaining several effects observed experimentally. We will also briefly comment on alternative theoretical formalisms and on

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extensions of the TMD approach. Finally, we will summarize recent phenomenological results of the approach, giving some conclusions and listing open points.

This contribution is intended as an introductory mini-review for a broad audience. Therefore, technical details will be skipped in favour of qualitative and phenomenological aspects. An extensive discussion on the subject and a complete list of references can be found e.g. in Refs. [2, 3].

TRANSVERSE SINGLE SPIN ASYMMETRIES: PHENOMENOLOGICAL MOTIVATIONS

Let us first recall what a transverse single spin asymmetry is. We will mostly consider the inclusive or semi-inclusive production of particles with moderately large transverse momentum in high-energy (un)polarized hadronic collisions. Typical examples are the inclusive (single and double) meson, photon, jet production in polarized pp collisions, the polarized SIDIS and DY processes. In all these processes there are two typical energy scales: 1) A large scale allowing for the use of perturbative QCD techniques and factorization schemes; 2) A small-intermediate scale, e.g. the transverse momentum of the observed hadron in SIDIS, of the order of few GeV at most, which keeps memory of the intrinsic parton motion inside the hadrons involved in the process.

For strong interactions, due to parity conservation and rotational invariance, only single spin asymmetries with the observed spin *transverse* to the production plane survive. In this case, the transverse single spin asymmetry A_N, also called left-right asymmetry, A_{LR}, is defined, e.g. for the inclusive process $A^\uparrow B \to C+X$, as:

$$A_N(A^\uparrow B \to C+X) = \frac{d\sigma^{A^\uparrow B\to C+X} - d\sigma^{A^\downarrow B\to C+X}}{d\sigma^{A^\uparrow B\to C+X} + d\sigma^{A^\downarrow B\to C+X}} = \frac{d\Delta_N\sigma(A^\uparrow B\to C+X)}{2\,d\sigma^{\rm unp}(AB\to C+X)}\,, \qquad (1)$$

where $d\sigma(A^{\uparrow,\downarrow}B \to C+X)$ is the transversely polarized invariant differential cross section for the process. An analogous definition holds for the transverse polarization of hyperons (e.g. Λs) inclusively produced in unpolarized hadronic collisions.

The reason why in pQCD these SSAs were expected to be negligible in inclusive high-energy hadronic processes is that in a standard leading-twist, collinear factorization approach, the origin of the hadronic SSA is brought back to the SSA arising at the *partonic* level, in the hard scattering process. Notice that by *collinear factorization approach* we mean the usual approach in which intrinsic parton motion is integrated over up to the hard scale of the process, giving rise to the evolution with scale of the soft functions involved, while it is neglected in the hard perturbative scattering.

Since the transverse spin states $|\uparrow,\downarrow\rangle$ can be written in terms of the usual $|\pm\rangle$ helicity states as $|\uparrow,\downarrow\rangle = (1/\sqrt{2})(|+\rangle \pm i|-\rangle)$, it is easy to see that a transverse single spin asymmetry is related to the imaginary part of the interference term between off-diagonal helicity amplitudes:

$$A_N \propto |\langle|\ldots|\uparrow\rangle|^2 - |\langle|\ldots|\downarrow\rangle|^2 \propto {\rm Im}\,\langle|\ldots|\pm\rangle\langle|\ldots|\mp\rangle^*\,. \qquad (2)$$

Since at tree level helicity amplitudes are real (up to an overall phase), and the pQCD massless qg coupling preserves helicity, it is easy to see that the partonic SSA, $\hat{a}_N$, is

strongly suppressed for large energy and transverse momentum scales [1]:

$$\hat{a}_N = \frac{d\hat{\sigma}^{a^\uparrow b\to cd} - d\hat{\sigma}^{a^\downarrow b\to cd}}{d\hat{\sigma}^{a^\uparrow b\to cd} + d\hat{\sigma}^{a^\downarrow b\to cd}} \propto \alpha_s(\hat{s})\,\frac{m_q}{\hat{s}} \sim \alpha_s(p_T)\,\frac{m_q}{p_T}\,. \tag{3}$$

Against this common wisdom, a huge amount of extremely puzzling results on transverse hyperon polarization in fixed-target unpolarized proton-nucleus collisions were collected during the 70s [4]. Since these data were at relatively low c.m. energy and transverse momentum, they were mainly interpreted as soft nonperturbative effects. Starting from the 90s, however, the E704 Collaboration at Fermilab measured huge SSAs for the process $p^\uparrow p \to \pi + X$ at $\sqrt{s} \sim 20$ GeV and $0.7 < p_T < 2.0$ GeV in the forward region ($x_F = 2p_L/\sqrt{s} > 0.4$) [5]. These results have been recently confirmed by the STAR Collaboration at RHIC [6] at much larger energies ($\sqrt{s} = 200$ GeV), again in the forward region (the pion SSA is almost negligible in the central and negative (pseudo)rapidity regions) and for p_T up to ~ 4 GeV. While leading-twist NLO collinear pQCD gives a fair account of the corresponding unpolarized cross sections in the same RHIC kinematical regime, it is unable to explain these huge SSAs. At that time, the results of the E704 collaboration triggered renewed theoretical and experimental efforts aiming at an understanding of these phenomena and of the physical mechanisms behind them.

Apart from the already mentioned RHIC extensive research program on spin physics [7], several azimuthal and single spin asymmetries have been studied and measured in polarized SIDIS processes by the HERMES-DESY [8] and COMPASS-CERN [9] collaborations, in the Drell-Yan process [10] and in almost back-to-back two-particle correlations in e^+e^- collisions at Belle [11]. In several cases these asymmetries result to be sizable and difficult to explain in the usual collinear approach.

THE TMD GENERALIZED PARTON MODEL APPROACH

From the theoretical point of view, two different approaches have been proposed:
1) The so-called twist-three collinear approach [12] works along the lines of the collinear pQCD factorization methods with the necessary inclusion of higher-twist quark-gluon correlation functions and a new class of twist-three parton distribution and fragmentation functions. While this method is less problematic from the point of view of the validity of the factorization procedure (in particular for single inclusive particle production in hadronic collisions) it has presently the problem that unpolarized cross sections (entering the denominator of the SSAs) can only be evaluated at leading twist level.
2) The second approach, which will be discussed at length in this contribution, is the so-called transverse momentum dependent QCD approach. In this approach, the intrinsic parton motion of partons inside initial hadrons and of produced hadrons w.r.t. the fragmenting final partons is not integrated over and is taken into account explicitly. Intrinsic parton motion plays a fundamental role in allowing for sizable azimuthal and SSAs as those discussed above: e.g., it is the possible azimuthal asymmetry in the distribution of unpolarized partons around the direction of motion of the parent, transversely polarized, proton which can explain the huge pion SSAs observed at Fermilab and RHIC

in the moderately large p_T region. This mechanism, called the Sivers effect, was first suggested by D. Sivers [13].

The first phenomenological realization of the TMD approach, that we will call generalized parton model, takes into account intrinsic parton motion both in the soft and hard components of the factorized cross section, including polarization effects and adopting the helicity formalism [14]. Factorization is assumed as a reasonable starting point. Later developments of the TMD approach [15] led to the so-called TMD color gauge invariant approach, where appropriate gauge links (Wilson lines), preserving gauge invariance, are introduced in the hadronic correlators: the corresponding (perturbative) gluon exchanges among partons before and after the hard scattering and the hadron remnants give rise to the imaginary interference terms required for a non vanishing SSA.

Since in this contribution we are mainly interested in the basic ideas of the formalism, we will limit our discussion to the generalized parton model approach, which is the most intuitive and easy to illustrate. In this approach, e.g. the invariant differential cross section for the doubly polarized single particle inclusive production in hadronic collisions, $A(S_A)\,B(S_B) \to C + X$, can be written as [14]:

$$\begin{aligned}\frac{E_C\,\mathrm{d}\sigma^{(A,S_A)+(B,S_B)\to C+X}}{\mathrm{d}^3\boldsymbol{p}_C} &= \sum_{a,b,c,d,\{\lambda\}} \int \frac{\mathrm{d}x_a\,\mathrm{d}x_b\,\mathrm{d}z}{16\pi^2 x_a x_b z^2 s}\, \mathrm{d}^2\boldsymbol{k}_{\perp a}\,\mathrm{d}^2\boldsymbol{k}_{\perp b}\,\mathrm{d}^3\boldsymbol{k}_{\perp C}\,\delta(\boldsymbol{k}_{\perp C}\cdot\hat{\boldsymbol{p}}_c)\\ &\times\; J(\boldsymbol{k}_{\perp C})\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\,\hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a})\,\rho^{b/B,S_B}_{\lambda_b,\lambda'_b}\,\hat{f}_{b/B,S_B}(x_b,\boldsymbol{k}_{\perp b})\\ &\times\; \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\,\hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b}\,\delta(\hat{s}+\hat{t}+\hat{u})\,\hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})\,, \end{aligned} \tag{4}$$

where: $x_{a,b}$, z, and $\boldsymbol{k}_{\perp a,b,C}$ are respectively the light-cone momentum fractions and the intrinsic transverse momenta of the initial partons a, b, inside hadrons A, B, and of the final observed hadron C inside the fragmentation jet of the scattered parton c; $J(\boldsymbol{k}_{\perp C})$ is a kinematical factor; $\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}$ is the helicity density matrix of parton a inside hadron A; the quantity $\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\,\hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a})$ encodes complete information on the polarization state of parton a and is related to the leading-twist TMD parton distribution functions which generalize the usual collinear PDFs; analogously for parton b inside hadron B; the $\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}$'s are the LO helicity scattering amplitudes for the hard partonic process $ab\to cd$; finally, $D^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})$ is the soft function describing the fragmentation process of the polarized parton c into the observed hadron C. In the sequel, for simplicity we will only consider the case of spinless or unpolarized final particles, for which this soft function simplifies to $D^{C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})$.

The polarization state of the initial parton a (and analogously for parton b) depends on the polarization state of the parent hadron A, which is fixed by the experimental conditions (we will have in mind spin-1/2 initial hadrons in the sequel) and on the soft (polarized) process $A(S_A) \to a(s_a) + X$:

$$\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\,\hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) = \sum_{\lambda_A,\lambda'_A} \rho^{A,S_A}_{\lambda_A,\lambda'_A}\,\hat{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}(x_a,\boldsymbol{k}_{\perp a})\,. \tag{5}$$

The transverse momentum dependent soft functions $\hat{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}$ are related to the leading twist hadronic correlator and the typical hand-bag diagrams for DIS. In principle there are 16 different functions. Rotational invariance and parity conservation for strong interactions reduce this number to eight independent TMD distribution functions (to be compared with the three fundamental parton distributions in the collinear approach). Bearing in mind that upper(lower) helicity indexes refer to parton(hadron) respectively, and that (off-)diagonal helicity combinations refer to (transversely)longitudinally polarized particles, these functions can be combined in a way which clarify their physical meaning; e.g. for quark partons: 1) $\hat{F}^{++}_{++} \pm \hat{F}^{--}_{++}$ are real quantities related to the unpolarized (longitudinally polarized) quark distributions; 2) $\hat{F}^{+-}_{+-} \pm \hat{F}^{-+}_{+-}$ are also purely real quantities and are related to the quark transversity distribution; 3) $\hat{F}^{++}_{+-} \pm \hat{F}^{--}_{+-}$ describe respectively an unpolarized (longitudinally polarized) quark inside a transversely polarized hadron and are associated to the Sivers function mentioned above and to the $g^{\perp}_{1T}$ distribution; 4) $\hat{F}^{+-}_{++} \pm \hat{F}^{+-}_{--}$ describe a transversely polarized quark inside an unpolarized(longitudinally polarized) hadron and are known respectively as the Boer-Mulders (BM) function [16] and the $h^{\perp}_{1L}$ distribution.

Notice that in the collinear, $\boldsymbol{k}_\perp$-integrated configuration, the only surviving functions are $\hat{F}^{++}_{++} \pm \hat{F}^{--}_{++}$ and $\hat{F}^{+-}_{+-}$, that is the three fundamental quark parton distributions, respectively the unpolarized, longitudinally and transversely polarized distributions. All other functions, due to the presence of a transverse polarization (either of the quark or of the hadron or both) w.r.t. the plane containing the quark and the parent hadron, can be azimuthally asymmetric around the direction of motion of the hadron. It is this azimuthal asymmetry, at the partonic level, that can give rise, in processes where a relatively small transverse momentum scale is measured, to a correlation among intrinsic motion and polarization effects which can survive at the hadronic level even at leading twist, as for example in SIDIS and Drell-Yan processes. For inclusive single particle production in pp collisions the situation is slightly more involved: in order to have a non vanishing asymmetry one needs to keep into account intrinsic parton motion also in the hard processes. This can cast some doubts on the validity of the factorization procedure and effectively makes the asymmetry *at hadronic level* a twist-three effect.

Analogous arguments can be used for the leading twist TMD parton fragmentation functions. In this case one finds that, for spinless or unpolarized particles, only two TMD functions survive: one related to the usual collinear unpolarized FF, and a second one, the Collins fragmentation function [17], which describes the azimuthal asymmetry in the distribution of hadrons (inside the fragmentation jet) around the direction of motion of the fragmenting parton. For spin-1/2 particles, e.g. hyperons, in close analogy with the distribution sector, there are instead eight independent leading twist, TMD fragmentation functions.

PHENOMENOLOGY

Let us now summarize and briefly comment on the TMD functions most relevant from the phenomenological point of view. Essentially there are two of them in the distribution sector and two in the fragmentation sector:

1) The chiral-even, naively T-odd, Sivers distribution function [13]:

$$\Delta \hat{f}_{q/p^\uparrow}(x,\boldsymbol{k}_\perp) = \hat{f}_{q/p^\uparrow}(x,\boldsymbol{k}_\perp) - \hat{f}_{q/p^\downarrow}(x,\boldsymbol{k}_\perp) = \hat{f}_{q/p^\uparrow}(x,\boldsymbol{k}_\perp) - \hat{f}_{q/p^\uparrow}(x,-\boldsymbol{k}_\perp)\,. \tag{6}$$

The Sivers function describes the azimuthal asymmetry in the distribution of unpolarized quarks around the direction of motion of the transversely polarized parent proton. It plays a relevant role for SSAs in polarized $AB \to C+X$, SIDIS and DY processes.
2) The chiral-odd, naively T-odd, Boer-Mulders distribution [16]:

$$\Delta \hat{f}_{q^\uparrow/p}(x,\boldsymbol{k}_\perp) = \hat{f}_{q^\uparrow/p}(x,\boldsymbol{k}_\perp) - \hat{f}_{q^\downarrow/p}(x,\boldsymbol{k}_\perp) = \hat{f}_{q^\uparrow/p}(x,\boldsymbol{k}_\perp) - \hat{f}_{q^\uparrow/p}(x,-\boldsymbol{k}_\perp)\,. \tag{7}$$

It describes the azimuthal asymmetry in the distribution of transversely polarized quarks around the direction of motion of the unpolarized parent proton, and plays a role for several azimuthal asymmetries in unpolarized $AB \to C+X$, SIDIS and DY processes.
3) The chiral-odd, naively T-odd, Collins fragmentation function [17]:

$$\Delta \hat{D}_{h/q^\uparrow}(z,\boldsymbol{k}_\perp) = \hat{D}_{h/q^\uparrow}(z,\boldsymbol{k}_\perp) - \hat{D}_{h/q^\downarrow}(z,\boldsymbol{k}_\perp) = \hat{D}_{h/q^\uparrow}(z,\boldsymbol{k}_\perp) - \hat{D}_{h/q^\uparrow}(z,-\boldsymbol{k}_\perp)\,, \tag{8}$$

which is related to the azimuthal asymmetry in the distribution of unpolarized hadrons around the direction of motion of the transversely polarized fragmenting quark. It plays a major role for azimuthal and spin asymmetries in (un)polarized $AB \to h+X$, SIDIS, DY, and $e^+e^- \to h_1h_2+X$ processes.
4) The chiral-even, naively T-odd, “Polarizing” fragmentation function [18]:

$$\Delta \hat{D}_{h^\uparrow/q}(z,\boldsymbol{k}_\perp) = \hat{D}_{h^\uparrow/q}(z,\boldsymbol{k}_\perp) - \hat{D}_{h^\downarrow/q}(z,\boldsymbol{k}_\perp) = \hat{D}_{h^\uparrow/q}(z,\boldsymbol{k}_\perp) - \hat{D}_{h^\uparrow/q}(z,-\boldsymbol{k}_\perp)\,, \tag{9}$$

describing the azimuthal asymmetry in the distribution of transversely polarized, spin-1/2 hadrons h (e.g. Λ hyperons), around the direction of motion of an unpolarized fragmenting quark. It plays a relevant role for the transverse hyperon polarization in unpolarized $AB \to h+X$ and SIDIS processes.

Over the last years the TMD generalized parton model has been extensively used in phenomenological analyses of a large set of measured azimuthal and single spin asymmetries, including data on $A_N(p^\uparrow p \to \pi+X)$ and from polarized SIDIS processes for the Sivers and Collins asymmetries, and from unpolarized DY and $e^+e^- \to h_1h_2+X$ processes, involving respectively, among others, the Boer-Mulders distribution and the Collins effect. In SIDIS processes, $\ell p \to \ell' h+X$, one looks at the inclusive production, in the virtual photon - target proton c.m. reference frame, of hadrons with transverse momentum P_{hT} of the order of 1 GeV, and measures the differential cross section as a function of P_{hT} and of the azimuthal angles of the hadron transverse momentum and transverse spin, measured w.r.t. the leptonic plane. We define the azimuthal asymmetries:

$$A_{S_B S_T}^{W(\phi_h,\phi_S)} = 2\langle W(\phi_h,\phi_S)\rangle = 2\,\frac{\int \mathrm{d}\phi_h \mathrm{d}\phi_S\, W(\phi_h,\phi_S)\,[\mathrm{d}\sigma(\phi_h,\phi_S) - \mathrm{d}\sigma(\phi_h,\phi_S+\pi)]}{\int \mathrm{d}\phi_h \mathrm{d}\phi_S\,[\mathrm{d}\sigma(\phi_h,\phi_S) + \mathrm{d}\sigma(\phi_h,\phi_S+\pi)]}\,, \tag{10}$$

where S_B, S_T are respectively the beam ($S_B = U,L$) and target ($S_T = U,L,T$) polarizations and $W(\phi_h,\phi_S)$ is an appropriate circular function, e.g. $W = \sin(\phi_h \mp \phi_S)$ respectively for the Sivers and the Collins effects [8, 9]. Analogously, in $e^+e^- \to h_1h_2+X$ processes, one looks at azimuthal correlations for two almost back-to-back hadrons (mainly

TABLE 1. A summary of the most interesting and experimentally accessible processes; for each of them, the TMD effects involved, the theoretical status and the usefulness in discriminating among different mechanisms are indicated.

Process	**Twist**	**Sivers**	**Collins**	**B-M**	**Pol. FF**	**Theor. Status**	**Discr. Power**
SIDIS ($\ell p \to \ell' h + X$)	2	•	•	•	•	****	****
Drell-Yan ($AB \to \ell^- \ell^+ + X$)	2	•		•		****	****
$e^+e^- \to h_1 h_2 + X$	2		•		•	****	****
$AB \to h + X$	3	•	•	•	•	**	**
$AB \to \gamma + X$	3	•		•		**	***
$AB \to h_1 h_2 + X$	2	•	•	•	•	***	***
$AB \to \text{jet} + X$	3	•		•		**	****
$AB \to \text{jet}\, h + X$	2	•	•	•	•	***	****
$AB \to \text{jet}\, \gamma + X$	2	•		•		***	****

pions) produced in the two-jet fragmentation of the high-energy parent $q\bar{q}$ pair. Again, in the e^+e^- c.m. frame, one can measure the asymmetry $\propto \langle \cos(\phi_1 + \phi_2) \rangle$, where ϕ_1 and ϕ_2 are the azimuthal angles of the two hadron momenta w.r.t. the plane containing the lepton beams and the jet thrust axis [11]. This asymmetry is related to the Collins effect in the fragmentation process.

Using combined data from SIDIS and e^+e^- processes, an updated set of parameterizations for the TMD Sivers [19] and (for the first time) transversity distributions and for the Collins function [20] has been extracted and made available for estimates of asymmetries in different processes and kinematical configurations accessible presently or in the near future by a number of experimental setups.

The case of single inclusive particle production in polarized pp collisions, which historically triggered the theoretical and phenomenological activity on transverse SSAs, is in fact much more involved: as we said before, the SSA is in this case a twist-three effect in a $1/p_T$ expansion, and several mechanisms, in particular the Sivers and Collins effects, can be present on the same basis. Moreover, for the distributions, the region of light-cone momentum fraction, x, covered by SIDIS data on azimuthal asymmetries is relatively low ($x \leq 0.3$). As a consequence, all parameterizations available for TMD distributions, in particular for the Sivers and transversity distributions, are plagued by large uncertainties in the large x region, which is the region relevant for the huge forward SSAs observed in pp collisions. From this point of view, the study of azimuthal asymmetries in the distribution of leading pions inside a jet in $p^\uparrow p \to \text{jet} + \pi + X$ processes can be quite useful since it allows, analogously to SIDIS processes, to disentangle among the various contributions. Work in this direction has been already done [21] and further extensions are currently in progress [22].

In Table 1 we summarize some of the most phenomenologically interesting processes, specifying the relevant mechanisms involved, their theoretical status concerning e.g. factorization, and their discriminating power, that is their usefulness in disentangling among the various mechanisms. Far from being a complete summary, this table gives however an idea of the present phenomenological activity in the field (see also Refs. [2, 3]).

OUTLOOK AND OPEN POINTS

Let us finally conclude by simply quoting some of the most relevant open points in this field and of the most promising developing topics: 1) For inclusive single and (partially) double inclusive particle production in hadronic collisions factorization remains to be proved and poses several difficulties; 2) Properties of evolution with scale of the TMD distribution and fragmentation functions are not well understood and much remains to be done on these aspects; 3) A consistent inclusion of all unknown soft factors (hopefully spin independent) from soft-gluon radiation has to be performed yet; 4) Related to this, the potential suppression of azimuthal asymmetries coming from Sudakov factors has been only partially investigated; 5) The role of parton offshellness and fully unintegrated parton correlation functions needs further study; 6) From a more phenomenological side, experimental tests of the universality (breaking?) of the TMD distributions, by carefully comparing different processes, are crucial at the present stage.

Hopefully in the near future more refined theoretical results, improved parameterizations and phenomenological constraints will help us in clarifying several points raised above, improving our understanding of the transverse structure and of parton orbital motion inside hadrons.

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